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Performance of Surface Modified-Zr Cladding Concept for Accident Tolerant Fuel

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1. Introduction

It is known that the Zr-based alloys have been used as fuel cladding in a nuclear reactor for a long time, because they have good corrosion resistance and mechanical properties and neutron economy in the normal operation conditions. But, development of enhanced accident tolerant fuel (ATF) cladding has started in the nuclear operators since Fukushima accident [1-3]. Enhanced ATF cladding can be defined as those that provide considerably increased response time in the event of nuclear reactor accident while providing similar or improved performance as the commercial Zr cladding during normal operation [1-3].

In addition, an enhanced accident tolerance include suppressed reaction with steam, resulting in lower hydrogen generation, while maintaining acceptable cladding geometry by increasing strength during the accidents. In light water reactors (LWRs), the fuel cladding should have excellent heat transfer and corrosion resistance characteristics, while preventing primary leakage of the fission products in fuel pellet. Regarding the fuel cycles, the manufacturing technology of Zr cladding and strip has been established in the industries because of the accumulation of manufacturing technologies over the last decades. And in the normal operation condition, the major performances such as corrosion, creep, irradiation growth, and wear are generally satisfied by using the commercial Zr alloy cladding. However, embrittlement problems associated with hydrogen uptake in to the Zr alloy cladding matrix by a corrosion reaction remain unresolved in normal and DBA conditions. In the accident conditions, various issues such as high-temperature oxidation, ballooning & burst, and low ductility after accidents are considered to be a big problem in the Zr alloy cladding. By a developing of advanced Zr-based alloys the performances in a normal condition are very improved when compared to the Zircaloys; whereas, the performances at high-temperature are not considerably improved due to the material limitation of Zr alloys. In addition, the failure possibility of fuel cladding during spent fuel storage is being treated as a pending issue due to the hydride reorientation [4]. After considering these problems, it is known that the ATF cladding must meet all of the conditions of the nuclear fuel cycle as well as the performance of the accidents.

Here, the new concepts of cladding have to check for the feasibility assessment regarding the fuel performance code, economic, operational safety, and environmental impacts. And new AFT cladding concepts must be capable of integration into the nuclear fuel cycle system to ultimately be accepted by utilities and vendors. The challenges to develop ATF cladding concept is dependent on the maturity of the technology. After considering the various ATF cladding concepts and technologies, KAERI focused on the surface modified-Zr cladding as a near term application [5]. This study deals with the development status of ATF cladding concepts in the world, and considered the surface modified-Zr cladding concept developed at KAERI in detail.

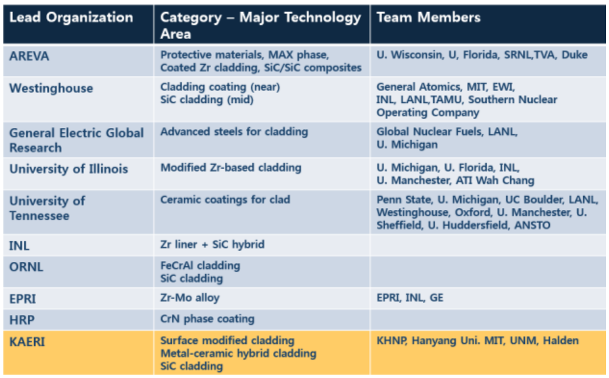
2. Methods and Results

2.1. Consideration of ATF cladding concepts

Fuel cladding provides the initial barrier to the release of fission products in nuclear fuel, and cannot considerably impact the fuel cycles. Fundamentally, the ATF cladding concept has to meet the current LWR design constraints, if it is to be applied to the current LWRs without a severe design change for near term application. Thus, the candidate concepts will be considered as the cladding criteria such as the compatibility, performance, economy, safety (DBA and BDBA), and fuel cycle in LWRs. It is known that the scientific and engineering challenges associated with nuclear technology result in a long, complicated fuel cladding qualification process. The development progress of new fuel concepts will consist of the design, manufacturing, testing, and evaluation. In addition, these steps will be repeated to obtain the optimum performance of the fuel cladding in the R&D strategy.

Table 1 shows the development status of ATF claddings, which are being carried out globally. Analysis of the tendency of ATF cladding development can be divided into cladding coating using Zr alloy and development of new materials such as Fe-based alloy and SiC_f/SiC. Here, the coating on the cladding and the development of Fe-based alloys are classified as near-term technology and SiC material is classified as long-term technology. Each of these cladding concepts has advantages and dis advantages, and research to solve this problem is proceeding in depth.

Table I: Summary of ATF Cladding Concepts



Lead Organization	Category – Major Technology Area	Team Members
AREVA	Protective materials, MAX phase, Coated Zr cladding, SiC/SiC composites	U. Wisconsin, U, Florida, SRNL,TVA, Duke
Westinghouse	Cladding coating (near) SiC cladding (mid)	General Atomics, MIT, EWI, INL, LANL,TAMU, Southern Nuclear Operating Company
General Electric Global Research	Advanced steels for cladding	Global Nuclear Fuels, LANL, U. Michigan
University of Illinois	Modified Zr-based cladding	U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang
University of Tennessee	Ceramic coatings for clad	Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO
INL	Zr liner + SiC hybrid	
ORNL	FeCrAl cladding SiC cladding	
EPRI	Zr-Mo alloy	EPRI, INL, GE
HRP	CrN phase coating	
KAERI	Surface modified cladding Metal-ceramic hybrid cladding SiC cladding	KHNP, Hanyang Uni. MIT, UNM, Halden

At KAERI, we analyze the technical merits and disadvantages related to the cladding performances and then develop surface modified-Zr cladding as a near-term application. The surface modified-Zr cladding is consisted of coating technology for improving oxidation resistance and oxide dispersion strengthened (ODS) technology for improving high temperature strength.

2.2. Fabrication of surface modified-Zircaloy-4 cladding tube samples

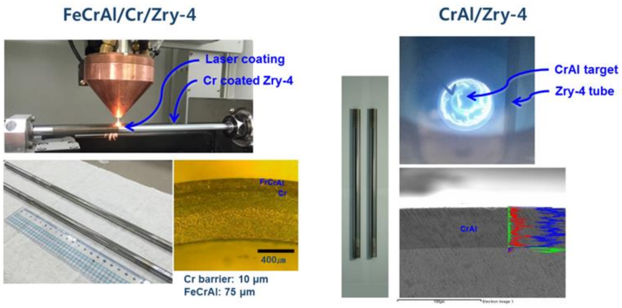


Fig. 1. Surface modification technology using 3D laser process and arc ion plating.

Fig. 1 shows the surface modification technology using 3D laser process and arc ion plating, which are developed at KAERI. The material coating to improve the oxidation/corrosion resistance on Zr cladding tube is performed by using the 3D laser process and arc ion plating, and partial ODS treatment is carried out by the 3D laser process. Regarding the coating materials, Cr-Al and FeCrAl alloys was selected as a coating material on Zircaloy-4 cladding. The Cr-Al binary alloy are being developed at KAERI by systematically evaluating various performance. And the FeCrAl alloy was developed at Sandvik for the purpose of improving corrosion resistance.

In case of the FeCrAl alloy coating on Zircaloy tube, the application of Cr to the intermediate layer is to suppress the eutectic reaction of Zr and Fe. Regarding the coating process of FeCrAl/Cr/Zry-4, the arc ion plating method is suitable for coating a thin Cr layer of about 10 to 20 microns think, and 3D laser coating using FeCrAl powder is preferably applied for coating a FeCrAl, because FeCrAl alloy has a magnetic property. In case of Cr-Al alloy coating, Cr-Al alloy powder with high melting point is not prepared for 3D laser coating at present and only arc ion plating using Cr-Al target is utilized.

2.3. Performance evaluation of surface modified-Zircaloy-4 cladding tube samples

A comprehensive evaluation of the cladding performance is very important regarding a licensing and commercial point of view. Therefore, the performance evaluation of the cladding should consider the items that were applied to the existing cladding development. In addition, in the case of the enhanced ATF cladding, there are factors to consider depending on the concept. In case of the surface modified-Zr cladding, verification of the adhesion property of the surface treatment layer is a very important item.

After the performance evaluation of the prepared samples, the surface modified-Zr cladding shows the improved performance (corrosion/oxidation, creep, wear, LOCA) and shows the reasonable performance (welding) when compared to commercial Zr cladding. Regarding the corrosion behavior, the flaking or galvanic corrosion was not observed in the samples between Zr matrix and coated material interface, which can be identified form the corroded sample appearances. A good corrosion/oxidation resistance of the Cr-Al binary alloy is the result of the stable oxide formations by an optimized compositional ratio between Cr and Al. It is confirmed that $CrAl_2O_4$ phase is stabilized under the normal operation condition and Al_2O_3 phase is stabilized under the accident conditions.

Improved mechanical properties such as creep and wear resistance were shown in the surface modified-Zr cladding, because the Cr-Al alloy had a higher strength than Zr alloy as well as the ODS structure layer had a good strength up to high temperatures. At the high-temperature, cladding strength is considerably improved by a uniform distribution of the Y_2O_3 particles although the thickness of ODS layer was 100 microns. An irradiation test of the surface modified-Zr cladding was reached up to 150 FPD in Halden research reactor. It was informed that KAERI rods (surface modified-Zr claddings) have operated normally and without any indication of failure during the operating period although there were 10 times of shot-down.

3. Conclusions

After considering the various ATF cladding concepts and technologies, KAERI focused on the surface modified-Zr cladding as a near term application. KAERI's ATF cladding concept was developed by a combination of the coating material evaluation and development and coating technology development. As a results of evaluating various performances, it was confirmed that the surface modified-Zr concept has superior performance to commercial Zr cladding. Based on these results, KAERI will carry out in-pile and out of-pile tests and steps for commercialization with industries.

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